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Seismic Safety Margins Research Program

Phase I Final Report—Subsystem Response (Project V)

L. C. Shieh, T. Y. Chuang, and W. J. O'Connell

Prepared for
U.S. Nuclear Regulatory Commission

LAWRENCE
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LABORATORY

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Seismic Safety Margins Research Program

Phase I Final Report—Subsystem Response (Project V)

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Prepared by

L. C. Shieh, T. Y. Chuang, and W. J. O'Connell

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ABSTRACT

This document reports on (1) the computation of the responses of subsystems, given the input subsystem support motion for components and systems whose failure can lead to an accident sequence (radioactive release), and (2) the results of a sensitivity study undertaken to determine the contributions of the several links in the seismic methodology chain (SMC)--seismic input (SI), soil-structure interaction (SSI), structure response (STR), and subsystem response (SUB)--to the uncertainty in subsystem response.

For the singly supported subsystems (e.g., pumps, turbines, electrical control panels, etc.), we used the spectral acceleration response of the structure at the point where the subsystem components were mounted. For the multiple supported subsystems, we developed 13 piping models of five safety-related systems, and then used the pseudostatic-mode method with multisupport input motion to compute the response parameters in terms of the parameters used in the fragility descriptions (i.e., peak resultant accelerations for valves and peak resultant moments for piping). Damping and frequency were varied to represent the sources of modeling and random uncertainty.

Two codes were developed: a modified version of SAPIV which assembles the piping supports into groups depending on the support's location relative to the attached structure, and SAPPAC, a stand-alone modular program from which the time-history analysis module is extracted.

On the basis of our sensitivity study, we determined that the variability in the combined soil-structure interaction, structural response, and subsystem response areas contribute more to uncertainty in subsystem response than does the variability in the seismic input area, assuming an earthquake within the limited peak ground acceleration range, i.e., 0.15 to 0.30g. The seismic input variations were in terms of different earthquake time histories.

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FOREWORD

The Seismic Safety Margins Research Program (SSMRP) is an NRC-funded, multiyear program conducted by Lawrence Livermore National Laboratory (LLNL). Its goal is to develop a complete, fully coupled analysis procedure (including methods and computer codes) for estimating the risk of an earthquake-caused radioactive release from a commercial nuclear power plant. The analysis procedure is based upon a state-of-the-art evaluation of the current seismic analysis and design process and explicitly includes the uncertainties inherent in such a process. The results will be used to improve seismic licensing requirements for nuclear power plants.

The SSMRP was begun in 1978 when it became evident that an accurate seismic risk analysis must simultaneously consider all the interrelated factors that affect the final probability of radioactive release. In the traditional design procedure, by contrast, each factor is usually analyzed separately. These closely coupled factors are:

- The likelihood and magnitude of an earthquake.
- The transfer of earthquake energy from a fault source to a power plant, a phenomenon that varies greatly with the magnitude of an earthquake.
- Interaction between the soil underlying the power plant and the structural response, a phenomenon that depends on the soil composition under the plant and the location of the fault source relative to the plant.
- Coupled responses of a power plant's buildings and the massive reactor vessels, piping systems, and emergency safety systems within.
- Numerous accident scenarios, which vary according to the types of failures assumed and the success or failure of the engineered safety features intended to mitigate the consequences of an accident.

A nuclear power plant is designed to ensure the survival of all buildings and emergency safety systems in a worst-case ("safe shutdown") earthquake. The assumptions underlying this design process are deterministic. In practice, however, these assumptions are clouded by considerable uncertainty. It is not possible, for example, to accurately predict the worst earthquake that will occur at a given site. Soil properties, mechanical properties of

buildings, and damping in buildings and internal structures also vary significantly among plants.

To model and analyze the coupled phenomena that contribute to the total risk of radioactive release it is therefore necessary to consider all significant sources of uncertainty as well as all significant interactions. Total risk is then obtained by considering the entire spectrum of possible earthquakes and integrating their calculated consequences. In the SSMRP this approach to risk analysis is embodied in the seismic analysis chain, comprising four steps: determining seismic input characteristics for a site, calculating the effects of soil-structure interaction, calculating major structure and subsystem response, and calculating probability of failure.

The seismic input consists of the earthquake hazard in the vicinity of a nuclear power station, defined by an estimate of the seismic hazard function (i.e., the relationship between the probability of occurrence and a measure of the size of an earthquake) and a description of the free-field motion. The soil-structure interaction link in the chain transforms the free-field ground motion into basemat or in-structure response, accounting for the interaction of the soil with the massive, stiff structures present at a nuclear power plant. Determination of the major structure response follows the soil-structure interaction step, where "major structure" commonly denotes a building, but may also include very large components. The final step in the traditional seismic analysis and design process is predicting subsystem structural response. An additional step in the SSMRP is the prediction of failure and subsequent risk of radioactive release.

In the SSMRP this methodology is implemented in three computer programs: HAZARD, which assesses the seismic hazard at a given site, SMACS, which computes in-structure and subsystem seismic responses, and SEISIM, which calculates structural, component, and system failure probabilities and radioactive release probabilities.

The SSMRP Phase I effort was organized into eight projects. In Project I, Unit 1 of the Zion Nuclear Power Plant was chosen as an appropriate "typical" plant. In Project II, we developed the tools and models, including HAZARD, necessary to describe probabilistically the seismic hazard at the Zion site and to generate the appropriate acceleration time histories. Soil-structure interaction was the subject of Project III, in which we provided as input to the first step in the SMACS calculational procedure the characterizations of soil, foundations, and structures at the Zion plant

necessary to an analysis of the coupled soil-structure system. Major structure models were developed in Project IV as necessary input to the SMACS computation carried out in Project VIII. In Project V, data were collected and models established for the pertinent piping subsystems to provide input to the SMACS computation. In Project VI we developed fragility curves--normal or lognormal distributions describing the probability of failure as a function of a critical response parameter--necessary for all components and structures whose failure is accounted for in the SEISIM fault trees. In Project VII the SEISIM computer program embodied event/fault trees to systematically describe the possible accident sequences that follow an earthquake and accepted as input the responses computed by SMACS, the set of fragility curves, and a seismic hazard curve for the Zion site to calculate the structural, component, and system failure probabilities and the probabilities of radioactive release. The SMACS computer code was developed in Project VIII to tie together the soil-structure interaction, structure response, and subsystem response calculations.

The results and technical products of each of the eight projects are described in separate volumes of the SSMRP Phase I Final Report.

This volume of the final report addresses the work performed under Project V, Subsystem Response. The NRC technical monitor for Project V was J. J. Burns. We would like to express our thanks to Enos H. Baker of EG & G, Inc., the editor of this volume, and to the members of LLNL's Technical Information Department Staff who contributed their efforts to its production.

EXECUTIVE SUMMARY

The Subsystem Response Project of the Seismic Safety Margin Research Program (SSMRP) used the fault trees developed by the Systems Analysis Project (Vol. 8) to identify the components and piping runs and branches that could potentially contribute to the failure of a piping system. Then the appropriate response parameters for these components and piping runs and branches were computed by the SMACS Project (Vol. 9) using the computer program SMACS, given the input motion computed for the subsystems supports. Also, as a part of the Subsystem Response Project, a sensitivity study was undertaken to determine the contributions of the several links in the seismic methodology chain (SMC)--seismic input (SI), soil-structure interaction (SSI), structure response (STR), and subsystem response (SUB)--to the uncertainty in subsystem response.

Subsystem Response Review. Before undertaking development of the necessary models and software, we solicited two extensive reviews of subsystem response methodologies. These reviews, provided by the Nuclear Services Corporation/Quadrex (NSC) and Engineering Decision Analysis Company (EDAC), achieved several aims:

- Reported on existing methods and methods under development for the seismic qualification of subsystems.
- Assessed the accuracy of available seismic analysis techniques to predict dynamic responses.
- Identified and quantified sources of random and modeling uncertainty in subsystem response determination.
- Recommended appropriate subsystem analysis techniques for the SSMRP.

As a result of these reviews, the multisupport input time-history technique was chosen for the piping response analysis.

Modeling. In constructing the 13 mathematical piping models needed for the response computations of the 5 safety-related systems identified in the fault trees, we made the following assumptions:

- Piping systems were assumed to be linear elastic.

- Piping supports, including rigid hangers and snubbers, were assumed to be rigid. (Two exceptions were the auxiliary feedwater model (inside containment) and the reactor coolant model, where appropriate spring rates were incorporated.)
- Constant and variable spring hangers were not included due to small stiffness compared to the stiffness of other restraints.
- Pipe whip restraints were not included in the model because gaps between the restraints and the pipe were assumed to be large enough to accommodate the seismic movement.

The effect of internal pressure on bend flexibility was included in the stiffness formulation of the elbows/pipe bends in the SAP4 code. In general, we used the pipe elements of SAP4 to define straight and curved pipes and equipment (if modeled) and boundary elements of SAP4 to simulate supports and restraints. However, in the model of the reactor coolant loops (including a portion of branch lines), we used truss and beam elements to describe equipment supports and stiffness/flexibility elements to represent the stiffness effects of the main steam lines and main feedwater lines. Also in the RCL model some pipe whip restraints with small gaps were modeled.

Analysis. After a review of the literature on spectral/time-history analysis techniques, we chose the pseudostatic-mode method with multisupport input motion instead of either the absolute displacement method or the datum acceleration and relative displacement method because it was the most efficient analytical technique for our purposes. The software to perform multisupport time-history analysis was developed by modifying the existing SAP4 code and by writing a new program named SAPPAC. The modified SAP4 code assembles the piping supports into groups depending on the support's location relative to the attached structure. This support grouping capability is essential for the multisupport input motion approach. The modified version of SAP4 also assembles the pipe-element mass and stiffness matrices and the pipe element-piping support coupling stiffness matrices, and then generates stress-displacement matrices in the process of modal extraction analysis. Pseudostatic modes are obtained by SAP4 static runs with no loads defined and a unit displacement imposed on each support group one at a time. SAPPAC implements the pseudostatic-mode method for performing the multisupport time-history analyses. By combining SAPPAC with the CLASSI program, the SMACS

code was produced. The information from SAP4 together with information on the piping components and valves to be analyzed are input to SMACS; the resultant output is the seismic responses of the piping systems.

Treatment of Uncertainties. Both random and modeling uncertainties are sources of uncertainty in piping system response. These sources of uncertainty influenced the piping system frequencies and damping values which in turn affected the subsystems responses. We used variations in frequency and damping to represent the sources of uncertainty for piping systems. Values of their variability were estimated from a limited review of published test results.

Sensitivity Study. In Phase 1, the sensitivity study explored the following question: Which areas of the SMC contribute most to the uncertainty in subsystem response? In a series of numerical experiments, we varied some SMC areas in order to represent their existing uncertainty while leaving the other areas fixed. Latin hypercube sampling (LHS) was used in each experiment to evaluate the corresponding response uncertainties.

In Phase 1 we evaluated two of the planned nine numerical experiments: (1) by varying all SMC input areas and (2) by varying seismic input only. We noted in the results that:

- Considerable variability occurred among different response points.
- Coefficients of variation (COVs) were larger for subsystems than for the basemat or structure.
- Subsystem response uncertainty was due more to the combined soil-structure, structural, and subsystem input uncertainties than to site earthquake-motion uncertainties within a defined earthquake ground acceleration range.

As a supplementary approach to response uncertainty analysis, we used first-order uncertainty propagation applied to a simplified subsystem. We noted that the response was quite sensitive to subsystem frequency and less so to damping.

Phase I Technical Results. For the singly supported subsystems (such as pumps, turbines, electrical control panels, etc.), the responses were obtained from the major structure responses at the locations where the components were mounted. For multiple supported subsystems such as piping systems, responses

were in terms of peak resultant accelerations for valves and peak resultant moments for piping components. Only the responses of the critical piping components (such as tees, nozzles, elbows/pipe bends, etc.) in the systems identified in the event/fault trees were computed.

For the Phase I demonstration calculations, response plots for over 1000 components were generated for each range of ground acceleration; therefore, only representative plots of interest are shown in the report. Each plot summarizes the dynamic responses, medians, and standard deviations of the logarithm of the response of the piping component to 30 earthquakes in each range of ground acceleration.

SECTION 1: INTRODUCTION

In the SSMRP a subsystem is any component or system whose behavior during a seismic event can be decoupled from the major structure response.

In Phase 1 of the SSMRP, the Subsystem Response Project had two primary objectives:

- To compute the response parameters of subsystems, given the input subsystem support motion for components and piping systems identified on the fault trees whose failure might lead to an accident condition. The subsystem responses were then used to calculate component failure probabilities and uncertainties.
- To perform a sensitivity study on the subsystem response parameters in order to provide guidance to systems analysis regarding the effects of uncertainty on the response.

Piping systems for nuclear power plants have been traditionally designed for seismic effects based on response-spectrum procedures using floor response spectra generated from time-history analyses of the structure. Since piping systems have multiple supports that are frequently located at different elevations, the input to the systems was specified by multiple sets of response spectra for each orthogonal direction of input motion. Currently, response spectra analyses of piping systems are often conducted on the assumption that all anchor and support points have a common base motion defined by the envelope spectra of all elevation spectra in a given direction. This penalizes segments of the piping in low seismic excitation areas of the structure, no matter how remote they are from high seismic excitation areas. The system stresses due to differential anchor or support displacement (considered to be statically applied) are then added to the stresses computed from the common base motion response spectrum analysis in the manner specified in the requirements of the ASME Boiler and Pressure Vessel Code, Section III, Division I for piping components.[1] Often, very conservative bounding-type computations are used to estimate the stresses due to differential support motion (such as assuming that the peak floor displacements of the different structures are 180° out of phase).

To eliminate any excessive design conservatism due to implicit assumptions in the analysis procedures, piping analysts are now considering the use of spectral or time-history analysis techniques that account for different input spectra at various support levels. Several authors have

considered the application of spectral methods to the problem of multisupport motion of piping systems.[2,3]

Thirteen piping models were developed to represent the five safety-related systems selected for the Phase I analysis (see Sec. 3 and Figs. 1 through 13). The responses were computed only for critical piping components such as nozzles, elbows, bends, reducers and tees, and valves identified as potential contributors to the failure of a system on the event/fault trees.

Given the support input motion from the in-structure response,[4] the subsystem responses were computed by SMACS[5] in terms of peak resultant accelerations for valves and peak resultant moments for piping components.[6] Only the peak resultant moment for the weakest piping component in each basic event is input to SEISIM.[7] For example, in Fig. 1 the pipeline number 1FW014-16" is represented by a basic event. A basic event refers to the event located at the bottom of the fault tree. This is the event that initiates the paths through the fault tree and is associated with the failure of basic components or piping systems.

Side studies were undertaken to examine modeling alternatives, available analysis techniques, and sources and impacts of uncertainty. Two important products of the side studies were the subsystem response review (Sec. 2) and sensitivity analysis (Sec. 6). The subsystem response review focused on discrete portions of the computational procedure and furnished guidance and insight as we developed our calculational methods. The sensitivity analysis explored the impact of uncertainties in the seismic methodology chain (SMC)[8] on the subsystem response uncertainty.

SECTION 2: SUBSYSTEM RESPONSE REVIEW

Before undertaking development of the necessary models and software, we solicited two extensive reviews of subsystem response methodologies.[9,10] These reviews, provided by EDAC and the NSC/Quadrex,

- Reported on existing methods and methods under development for the seismic qualification of subsystems.
- Assessed the accuracy of available seismic analysis techniques to predict subsystem dynamic responses.
- Identified and quantified sources of random and modeling uncertainty in subsystem response determination.
- Recommended appropriate subsystem analysis techniques for the SSMRP.

The EDAC report documented the state of the art in seismic qualification of nuclear power plant components and subsystems by analysis and testing, and identified the sources and magnitude of the uncertainties associated with analysis and testing methods.[9] Uncertainties were defined in probabilistic terms for use in probabilistic seismic risk studies. Recommendations were made for the most appropriate subsystem response analysis methods to minimize response uncertainties. Although the general effect of nonlinearities on subsystem response was discussed, recommendations and conclusions were based principally on linear elastic analysis and testing.

The NSC/Quadrex report also discussed the current status of subsystem seismic evaluation techniques and uncertainties in nuclear power plant design.[10] A classification system was developed in order to fit subsystems into similar, more manageable groups. Various methods of subsystem evaluation were discussed and significant differences were pointed out. In order to quantify the uncertainties in subsystem analysis, questionnaires were sent to a number of industry experts who assigned conditional uncertainty probabilities to different categories of subsystems.

As a result of the review, the multisupport input time-history technique was chosen for the piping response analysis in the SSMRP Phase I.

SECTION 3: MODELING

Before constructing our own piping models, we reviewed and summarized information on available models of piping systems of the Zion Nuclear Power Plant, including the main steam and main feedwater system, auxiliary feedwater system, residual heat removal system, service water system, safety injection system, component cooling water system, containment spray system, and reactor coolant system.[11] Then, with this information and using state-of-the-art piping modeling techniques, we constructed the 13 mathematical models needed for response computations.

The following safety-related systems were identified as potential contributors to the system failure on event/fault trees for the Phase I piping analyses.

1. Auxiliary Feedwater System (AFWS): This system provides emergency cooldown capability on loss of the normal Main Feedwater System. Two models were generated (Figs. 1 and 2). The piping runs from the auxiliary feedwater pumps to steam generator 1-A.

2. Service Water (SW) System: This system supplies all the equipment cooling water for the plant, including the emergency shutdown requirements. Three models were generated (Figs. 3 through 5). Only the portion of piping which provides the backup water supply to the auxiliary feedwater system was modeled.

3. Residual Heat Removal (RHR) System and Safety Injection (SI) System: The RHR system removes residual heat from the core and reduces the temperature of the reactor coolant system during the second phase of plant cooldown. The SI system is designed to cool the core and to limit the metal-water reaction to an insignificant amount. Six models were created for this system (Figs. 6 through 11). The entire RHR System identified in the fault trees was included in the model, while only the portion of the Safety Injection piping which connects to the RHR System was modeled.

4. Reactor Coolant System (RCS): This system transfers the heat generated in the core to the steam generators where steam is generated to drive the turbine generators. Two models were generated: one for the reactor coolant loop (RCL) piping (Fig. 12) and one for the pressurizer relief piping (Fig. 13). The reactor coolant loop model contains all four main reactor coolant loop piping systems, six branch lines (the pressurizer surge line, the residual heat removal line, the bypass line, the safety injection line, and

two pressurizer spray lines), and all major equipment (including the reactor pressure vessel, four steam generators, four reactor coolant pumps, and a pressurizer). Each coolant loop model includes three sections of pipe--a hot leg from the reactor pressure vessel to the steam generator, a crossover leg to the reactor coolant pump, and a cold leg back to the reactor pressure vessel. The second model was for the pressurizer relief piping, which includes the piping between the pressurizer and the pressurizer relief tank, and the pressurizer itself.

Several assumptions were made in the development of the models:

- Piping systems were assumed to be linear elastic.
- Piping supports including rigid hangers and snubbers were assumed to be rigid except for AFWS and RCL piping models, where appropriate spring rates were incorporated.
- Constant and variable spring hangers were not included due to their small stiffness compared to the stiffness of other restraints.
- Pipe whip restraints were not included in the model because gaps between the restraints and the pipe were assumed to be large enough to accommodate the seismic movement.

The effect of internal pressure on bend flexibility was included in the stiffness formulation of the elbow/pipe bend in the SAP4 code. In general, we used the pipe elements of SAP4 to define straight and curved pipes and equipment (if modeled) and the boundary elements of SAP4 to simulate supports and restraints. However, in the model of reactor coolant loops (including a portion of branch lines), we used truss and beam elements to describe equipment supports and stiffness/flexibility elements to represent the stiffness effects of the main steam lines and main feedwater lines. Also in the RCL model some pipe whip restraints with small gaps were modeled. (For details of this model, refer to the report on reactor coolant loop modeling by Sargent and Lundy Engineers.)[12]

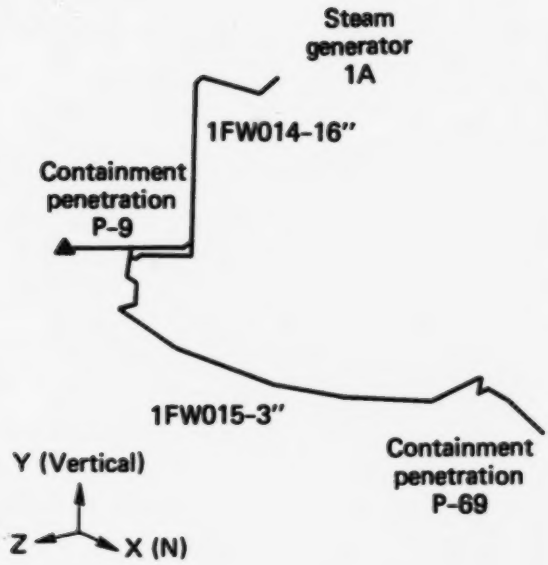


Fig. 1. Model of the AFW (inside containment) piping configuration.

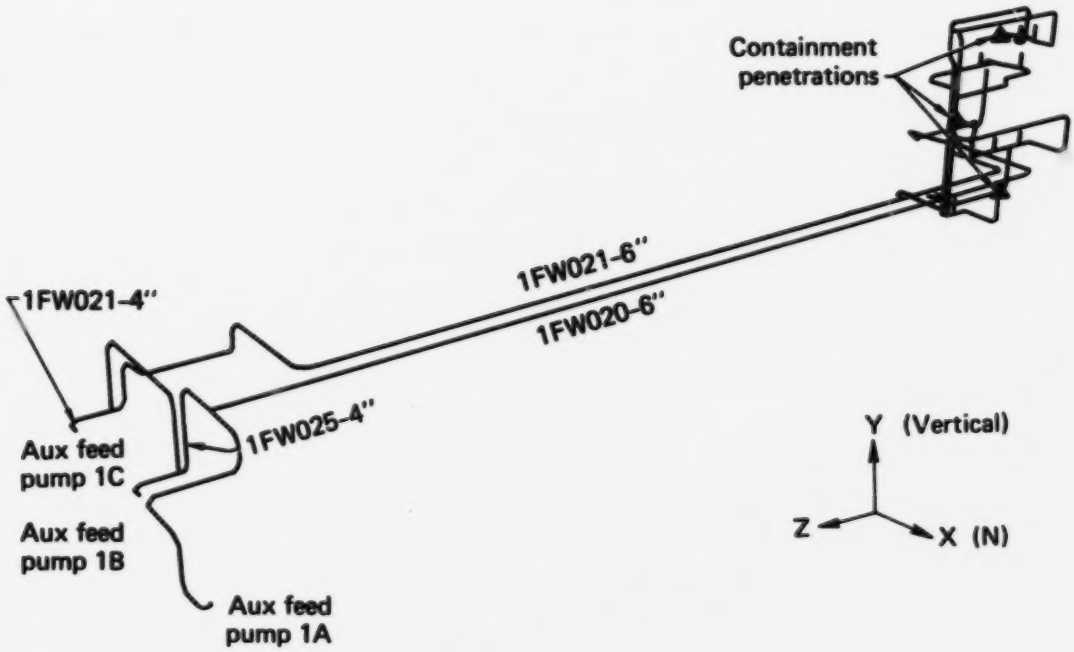


Fig. 2. Model of the AFW (outside containment) piping configuration.

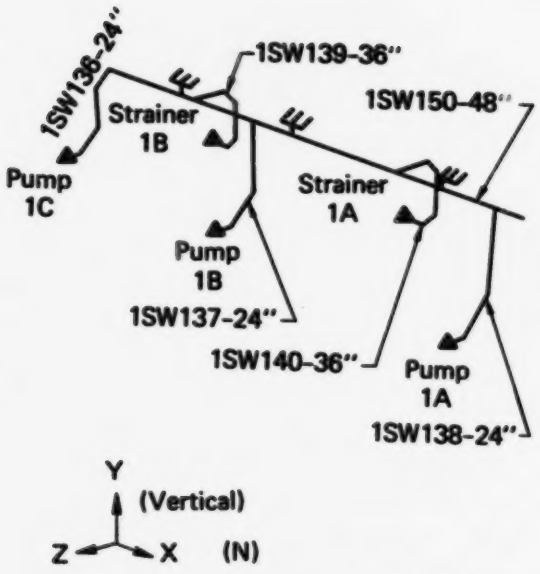


Fig. 3. Model of the SW pump discharge piping configuration.

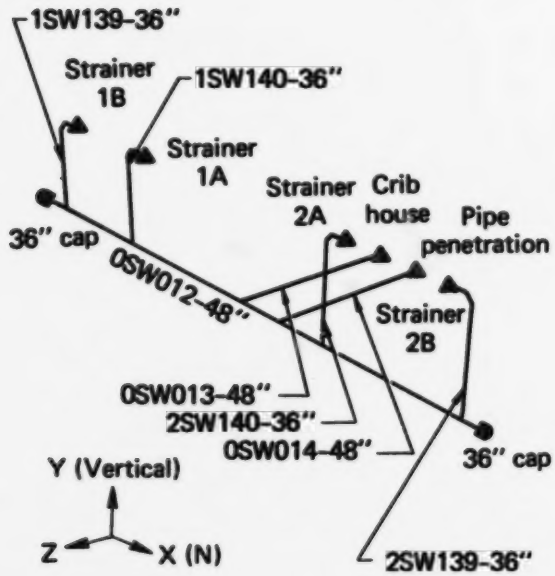


Fig. 4. Model of the SW strainer piping configuration.

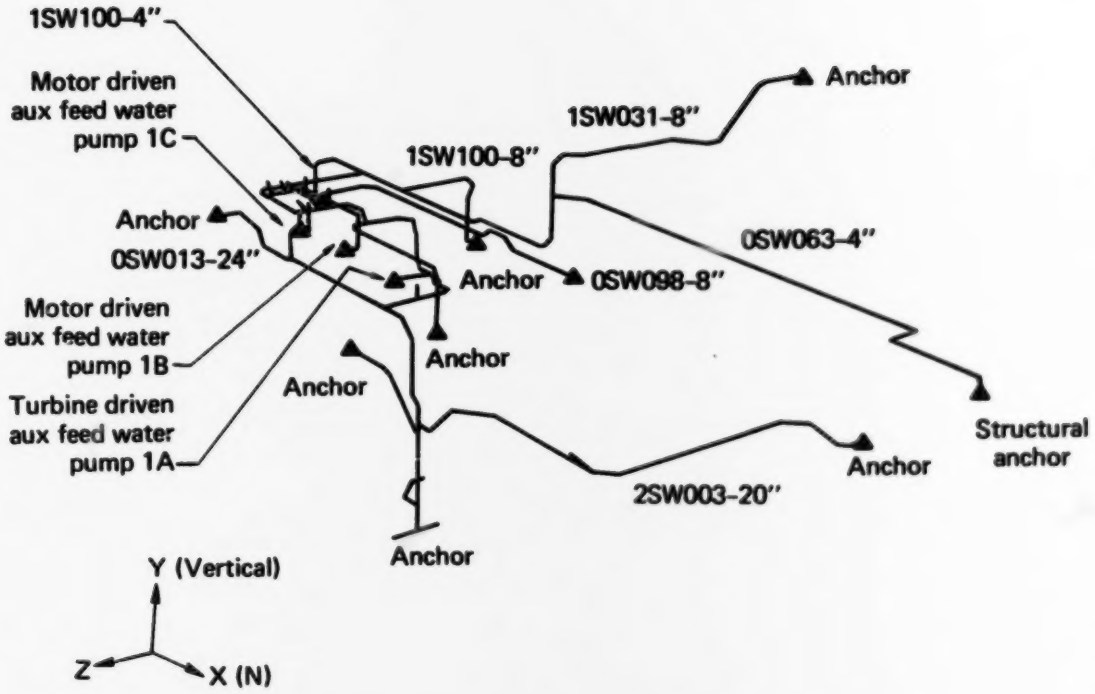


Fig. 5. Model of the SW to the AFW pumps piping configuration.

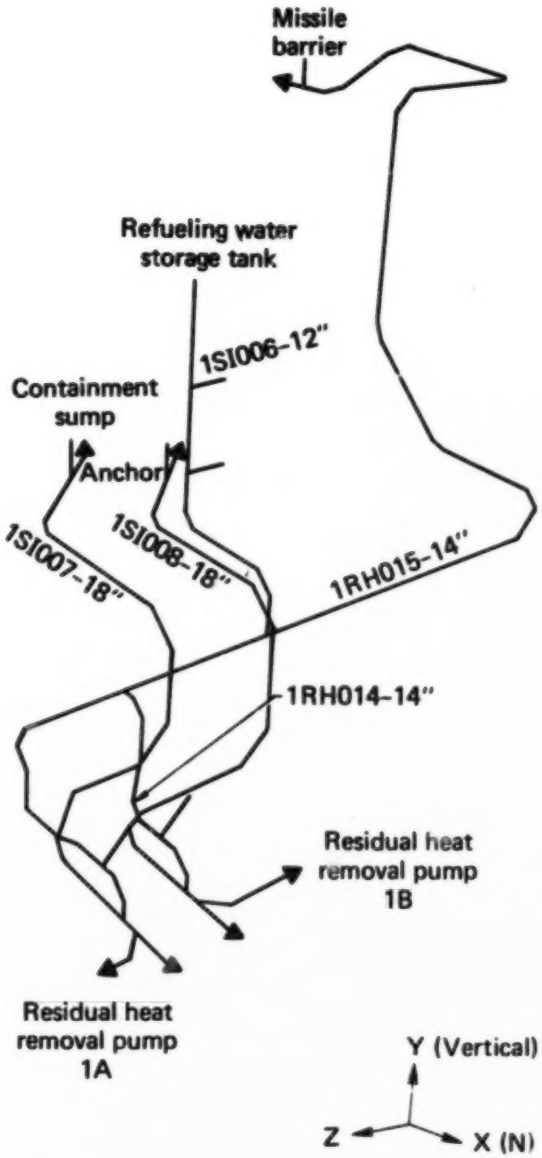


Fig. 6. Model of the RHR pump suction piping configuration.

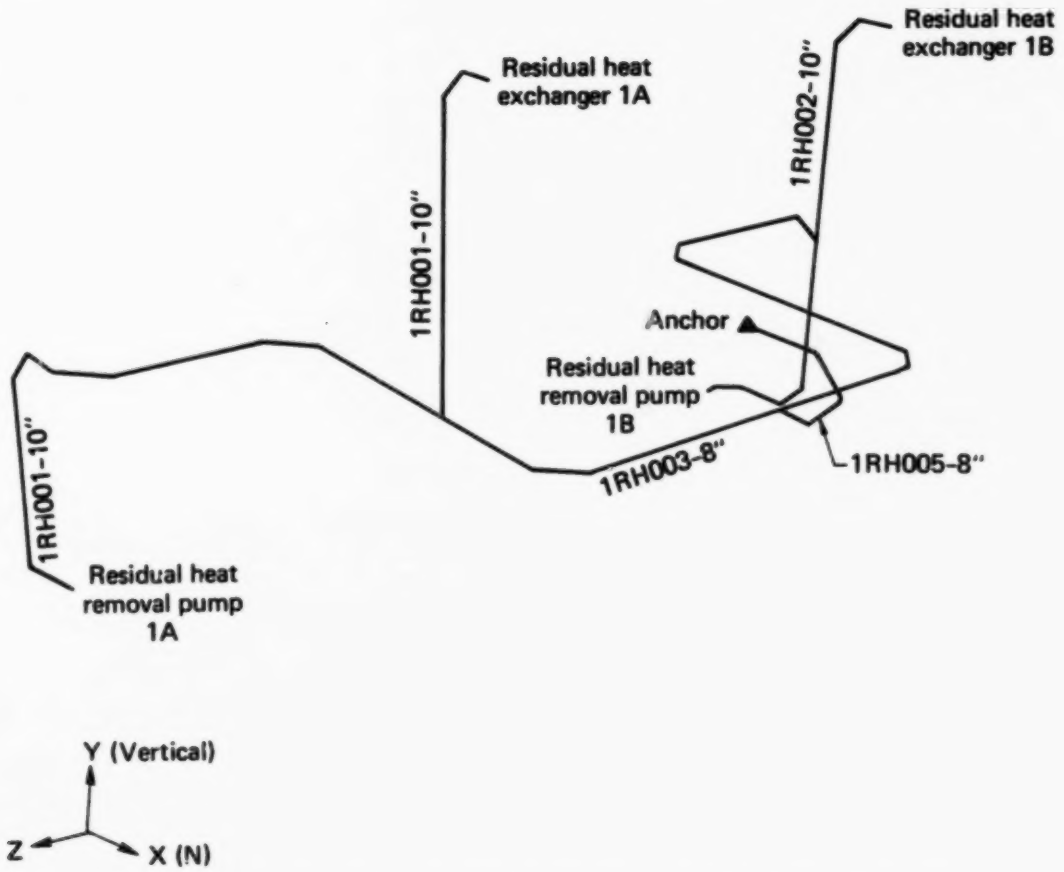


Fig. 7. Model of the RHR pump discharge piping configuration.

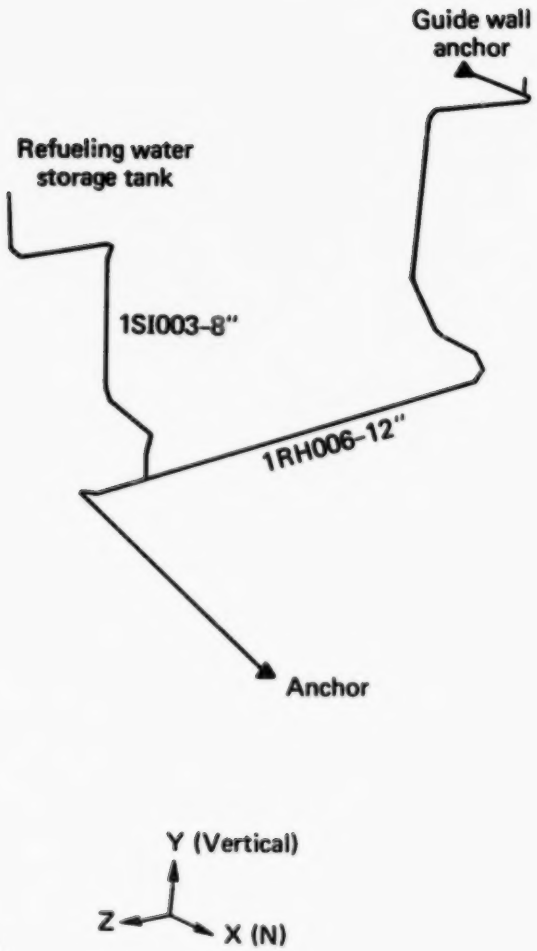


Fig. 8. Model of the RHR and the SI-1 piping configuration.

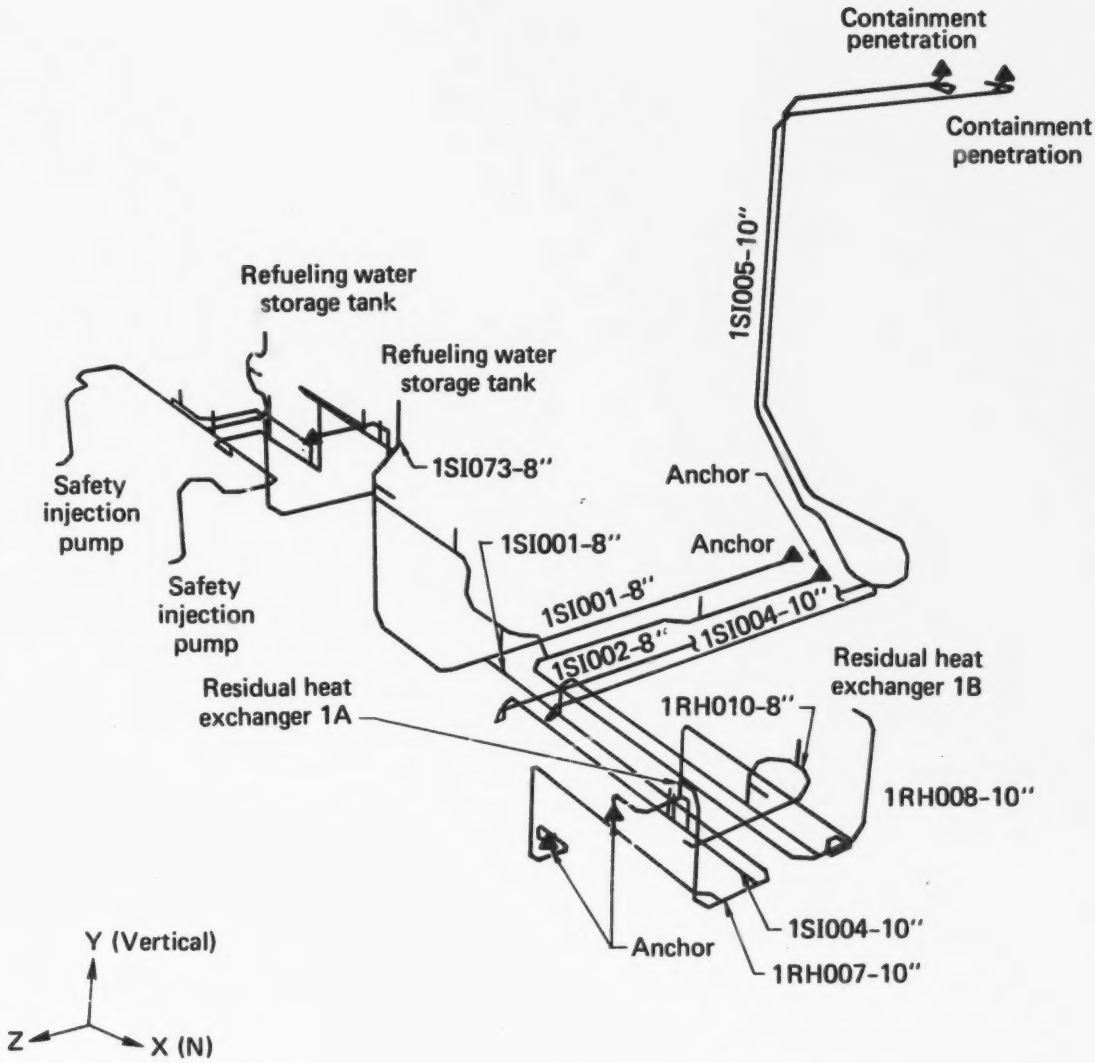


Fig. 9. Model of the RHR and the SI-2 piping configuration.

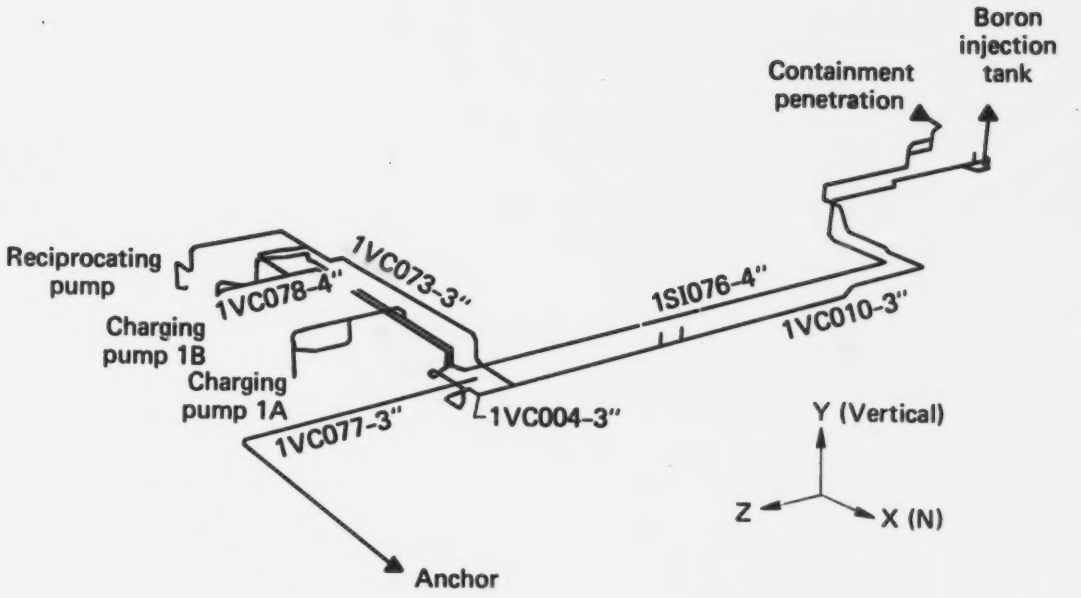


Fig. 10. Model of the charging pump discharge piping configuration.

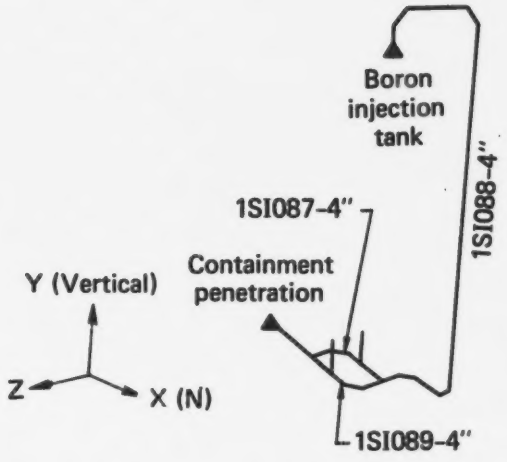


Fig. 11. Model of the safety injection piping configuration.

RPV (reactor pressure vessel)
SG (steam generator)

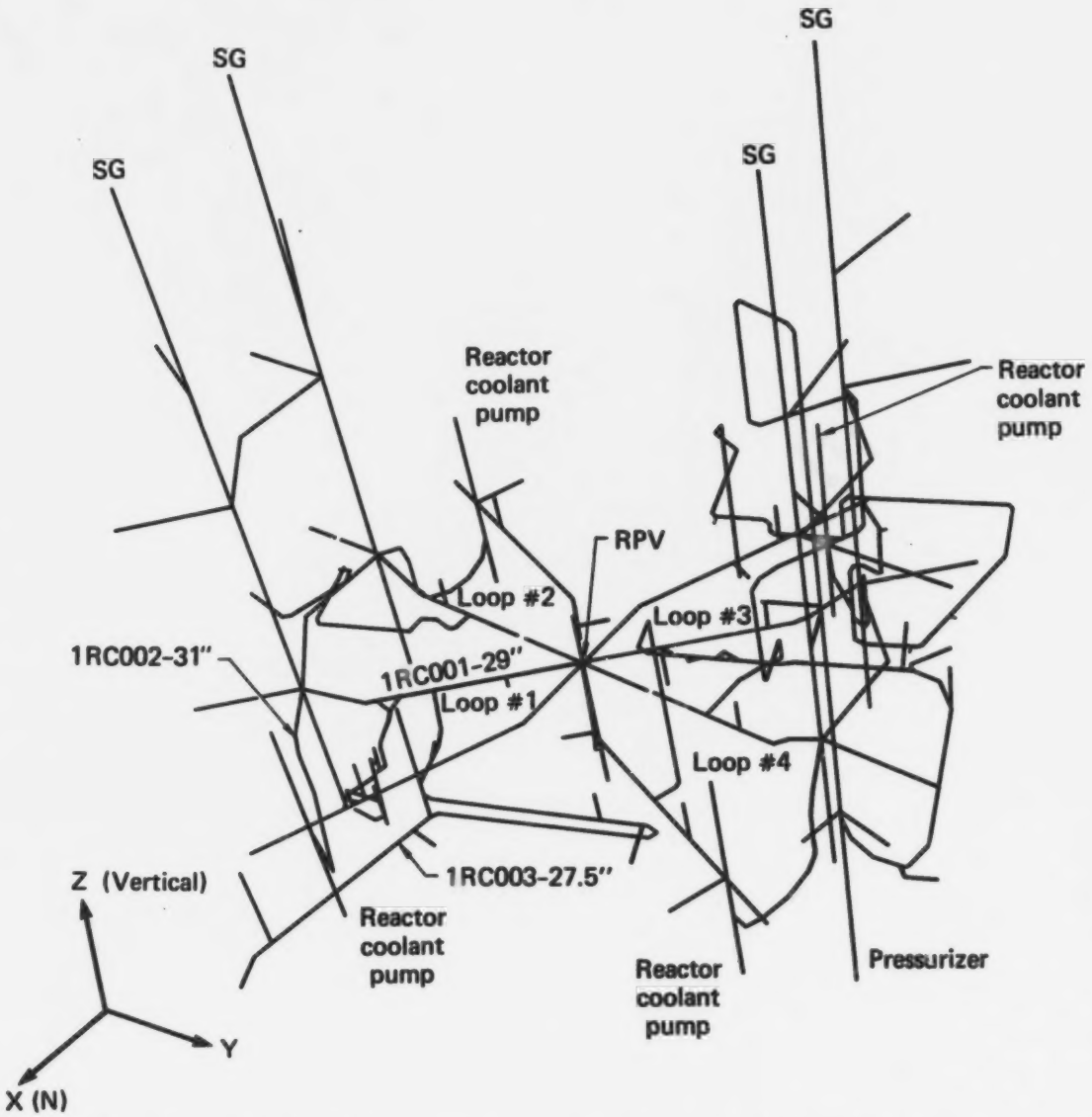


Fig. 12. Model of the reactor coolant loop piping configuration.

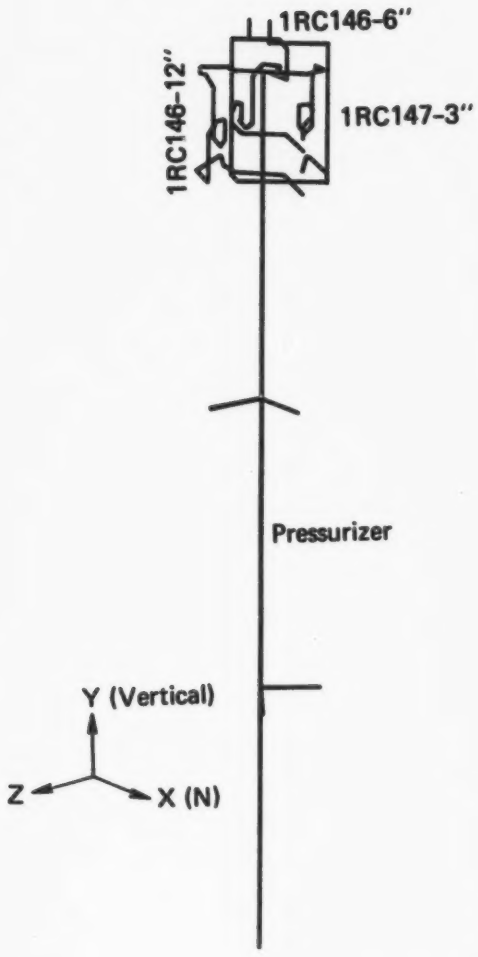


Fig. 13. Model of the pressurizer relief piping configuration.

SECTION 4: ANALYSIS

After reviewing the literature on spectral/time-history analysis techniques, we chose the pseudostatic-mode method with multisupport input motion for our analysis. The required software was developed by modifying the existing SAPIV code[13] and by writing a new program named SAPPAC.[14] The modified SAPIV code, SAP4, assembles the piping supports into groups depending on the support's location relative to the attached structure.[15] This support grouping capability is essential for the multisupport input motion approach. The SAP4 code also assembles the pipe element mass and stiffness matrices and the pipe element-piping support coupling stiffness matrices, and then generates stress-displacement matrices in the process of modal extraction analysis. Pseudostatic modes are obtained by SAP4 static runs with no loads defined (see Eq. 3) and a unit displacement imposed on each support group one at a time. SAPPAC implements the pseudostatic-mode method for performing the multisupport time-history analyses. By combining the response module of SAPPAC with the CLASSI program,[16] the SMACS code was produced.

All the information from SAP4 together with information on the piping components and valves to be analyzed are input to SMACS. The resultant output is the seismic responses of the piping systems.

The following is a brief description of the pseudostatic-mode method. The partitioning of a subsystem's absolute displacement into active values (x_1) and controlled support values (x_2) leads to the following equation of motion:

$$M_{11}\ddot{x}_1 + C_{11}\dot{x}_1 + K_{11}x_1 = -C_{12}\dot{x}_2 - K_{12}x_2 \quad , \tag{1}$$

where the coupling mass matrix (M_{12}) is assumed to be zero, and

M_{ij} = partitioned mass submatrix of a subsystem
C_{ij} = partitioned damping submatrix of a subsystem
K_{ij} = partitioned stiffness submatrix of a subsystem.

Let

$$x_1 = x_1^s + x_1^d \quad , \tag{2}$$

where

$$K_{11}x_1^s = -K_{12}x_2 \tag{3}$$

defines the pseudostatic responses $x_1^s(t)$ of the active nodes and where x_1^d are the dynamic displacements of the active nodes. Substituting Eqs. 2 and 3 into Eq. 1 with the assumption of negligible coupling and pseudostatic damping forces, i.e., $C_{12}\dot{x}_2 + C_{11}\dot{x}_1^s = 0$, we obtain

$$M_{11}\ddot{x}_1^d + C_{11}\dot{x}_1^d + K_{11}x_1^d = -M_{11}\ddot{x}_1^s \ . \tag{4}$$

If we expand the dynamic displacements in terms of the fixed-base modes

$$x_1^d = \phi y \ , \tag{5}$$

where ϕ is the eigenvector matrix of the active nodes, and y is the generalized dynamic coordinate of the active nodes, we recognize

$$\phi^T K_{11}\phi = \omega^2 \text{ (diagonal)} \ ,$$

$$\phi^T M_{11}\phi = I \text{ (identity matrix)} \ , \tag{6}$$

and

$$\phi^T C_{11}\phi = 2(\xi)(\omega) \text{ (diagonal)} \ ,$$

where ξ is the critical damping ratio matrix, and ω is the eigenvalue matrix of the active node. Combining Eqs. 3 through 6, the final expression is

$$\ddot{y} + 2(\xi)(\omega)\dot{y} + \omega^2 y = (\omega^2)^{-1}\phi^T K_{12}\ddot{x}_2 \ . \tag{7}$$

We solved Eq. 7 for the generalized coordinate responses by the piecewise exact integration method of Nigam and Jennings, given the input motion specified by the three orthogonal components of the absolute acceleration time history for each support group.[17] Then the subsystem absolute displacements x_1 can be obtained by Eq. 2 with the aid of Eq. 5.

SECTION 5: TREATMENT OF UNCERTAINTIES

Sources of uncertainty in the piping subsystem response include both random uncertainties and modeling uncertainties.[9,10] Random uncertainties include material and geometric property uncertainties. For example, the location of supports affects frequency through span length. Elbow flexibility, which depends on geometry, material, pressure, etc., affects frequency. Tests on elbows indicated that the ASME code flexibility factor formula was accurate in the mean, but results varied from 5 to 20% about the mean.[18]

Modeling uncertainties include the limitations of modeling assumptions such as linearity, supports without gaps, decoupling of piping systems from the structural analysis, and lumped-mass spacing. Reference 7 contains some illustrative calculations on how decoupling affects the piping frequency results. These sources of uncertainty together influence the piping system frequencies and damping values, which then affect the results of interest, i.e., nodal accelerations and pipe element moments or forces. At the point of input to the calculations, we varied the frequency and damping to be able to calculate the impact of the input uncertainties on the final outputs.

As a focal point for representing subsystem uncertainty in our calculational model, we reviewed the dynamic test results of two studies that focused on piping damping values as they vary with stress, deformation, etc.,[19,20] and two reports that compared the measured to the calculated piping frequencies.[21,22] The differences in frequency ranged from 5% to as high as 35%. Some measured frequencies and mode shapes were not included in the calculational model because of support gaps, snubbers not locking during low amplitude vibration, etc. The accuracy of determination of frequencies is limited, whether approached via tests or via geometric and material data with dynamic modeling. For our modeling of the Zion plant piping, we estimated the coefficient of variation (COV) of the modeled frequency values to be 0.5. We intended that this estimated value include the variability observed between the calculated and measured values obtained from dynamic tests and from our additional modeling uncertainty based on our modeling assumptions, limited types of data used in the models, and lack of an alternative data source of dynamic tests on specific pipes.

Damping values measured in the referenced tests showed substantial scatter, plus variations with stress or deflection level. In applying these

values to our models of the Zion plant, we estimated a median damping of 2% of critical--since the stress level in an SSE earthquake is far below yield--and a COV of 0.7. As in the frequency case, our COV estimate was intended to include both the variability observed in tests and any systematic differences in the specific Zion piping systems for which we did not have dynamic test data.

SECTION 6: SENSITIVITY STUDY

6.1 APPROACH

In our attempt to determine which areas in the SMC contribute most to uncertainty in subsystem response due to earthquakes, we computed the effects of the SMC input uncertainties on the response uncertainty and then determined the relative influences of the different input areas. Early in the program, each project reviewed its SMC area and described the types of random and modeling uncertainties and their impact on the response results of that stage of the analysis chain. To compare the effects of these areas on a common scale, we conducted a formal uncertainty analysis. This analysis consisted of numerical experiments utilizing the Zion Nuclear Power Plant model, the dynamic response analysis code SMACS, and an experimental design to determine:

- Subsystem response uncertainty, given the input uncertainties present in all the SMC areas.
- Sensitivity of the response uncertainty to the input uncertainties.
- Relative ranking of the uncertainties in the various SMC areas according to their importance to the uncertainty in the response.

We used the same method for representing uncertainty in the SMC as was used in the on-line calculations. (On-line calculations are defined as computations leading directly toward producing probability of release results.) A best-estimate model of the Zion site soil, structures, and piping systems was developed first. Key parameters were then considered to be random variables to represent the uncertainties. The variability in seismic input motion was represented by using a group of 90 synthetic time histories.[23] The estimates of the uncertainties for the parameters were as in the on-line calculations.

To separate the influences of the different input areas on the response uncertainty, we used a series of repeated evaluations, holding some input parameters fixed and allowing some others to be varied (see Table 1). For each assumed set of SMC uncertainties, the corresponding dynamic response uncertainties were estimated using the Latin hypercube sampling (LHS) method. One advantage of the LHS over purely random sampling is that it spreads out the selection fairly evenly over the probability distribution of each variable considered separately. Estimators based on LHS have smaller variances than estimators based on a simple random sample.

TABLE 1. Experimental design for investigating the SMC contributors to uncertainty in subsystem response.

Experiment No.	SMC area			
	SI	SSI	STR	SUB
1	V	V	V	V
2	V	V	V	F
3	V	V	F	F
4	V	F	F	F
5	V	F	V	V
6	V	F	F	V
7	V	V	F	V
8	V	F	V	F
9	F	V	V	V

NOTE: V means key parameters varied. F means key parameters fixed at median values, except for No. 9, which was fixed at a single seismic input time history.

Given the sample of inputs, we obtained a corresponding sample of responses through our deterministic dynamic response computation. We then computed the statistics of this sample of responses to get an estimate of the response mean, standard deviation, and COV. Increasing the number of sampled values of the response improved the accuracy of the estimates of the mean, standard deviation, etc. The present study used 90-member LHS sets.

The dynamic analysis models and methods were the same as in the on-line calculations. The soil medium was represented by three horizontal layers over a relatively stiff half space. Two separate embedded foundations were used--one for the containment structures and one for the auxiliary building. The containment basemat has two structures on it: the prestressed containment shell and the internal concrete structure which supports a four-loop PWR nuclear steam supply system. The subsystems examined in this study were (1) the auxiliary feedwater piping from steam generator to the containment, (2) residual heat removal and safety injection piping in the auxiliary building, and (3) reactor coolant loops including a portion of branch lines.

The continuum linear analysis method with substructuring was used for the soil-structure interaction[24] and structural response analysis.[4] The

process started with the calculation of modal characteristics of fixed-base structures and the calculation of foundation impedance and scattering matrices. Modal superposition was then used to calculate the dynamic response at any point within the structure. For the piping systems, we used modal time-history analysis with multisupport input motions.

For the free-field seismic motion at the site, we used 90 synthetic 3-component earthquakes.[23] These earthquakes had peak horizontal acceleration ranging from 0.15 to 0.30g. Spectral variability was retained.

In another approach to response uncertainty analysis, we used first-order uncertainty propagation. This approach, in a simple case with one parameter, computes as the product of the input parameter's uncertainty times the response's sensitivity to that parameter. The response sensitivity is the slope of the response function, which can be mapped out as a function of the inputs. We used this method to gain insight into a simplified case consisting of a one-mode subsystem mounted on the containment building basemat. This application is intended to complement our principal approach, LHS, in exploring the influence of subsystem parameter uncertainty on response uncertainty.

6.2 RESULTS

The estimated input uncertainties and the approaches used are described in Table 2 and Secs. 5 and 6.1. The effects of the SMC parameters on the subsystem response uncertainty were explored by (1) numerical experiments with LHS and (2) first-order uncertainty propagation.

Using the first approach, we designed a series of numerical experiments (see Table 1) and evaluated two input experiments: (1) by varying all SMC input areas and (2) by varying seismic input only (see experiments No. 1 and No. 4 of Table 1).

For input case 1, the response βs (standard deviations of the logarithm of the response) and COVs of the responses for a large number of response locations are plotted in Fig. 14. The horizontal axis (response number) represents a coarse sorting of different responses into groups (from left to right):

- Free field - peak or spectral acceleration components (response Nos. 1 through 12).

TABLE 2. Key SMC parameters, their distributions and coefficients of variation.

SMC area	Parameter	Type of distribution	Coeff. of variation (COV)
Seismic input	(a)	(a)	0.25 - 0.45[b]
Soil	Shear modulus	Lognormal	0.5
	Material damping	Lognormal	1.0
Structure	Frequency	Lognormal	0.5
	Damping	Lognormal	0.7
Subsystem	Piping frequency	Lognormal	0.5
	Piping damping	Lognormal	0.7

[a]A sample of time histories is used.
[b]COV of spectral responses in the sample.

- Basemat - peak or spectral acceleration components (response Nos. 16 through 27).
- Major structure nodes - peak or spectral acceleration components (response Nos. 31 through 161).
- Piping nodes - peak resultant accelerations (response Nos. 165 through 184).
- Piping elements - peak resultant moments (response Nos. 188 through 283).

We noted in the results:

- Considerable variability among different response points.
- Larger COVs for subsystems than for the basemat or structures.

The results for input case 2--varying seismic input only--are shown in Fig. 15. We note that the subsystem βs and COVs are greatly reduced compared to case 1; they now remain on the same size order from the free-field seismic input through the structures and subsystems. We infer that subsystem response uncertainty is generally more a function of the combined soil-structural, structural, and subsystem input uncertainties than of site earthquake motion uncertainties within a defined earthquake amplitude range.

We are conducting additional computational experiments to separate the contributions of the three SMC areas which have been treated jointly thus far. We expect different trends for individual subsystems and nodes. Some

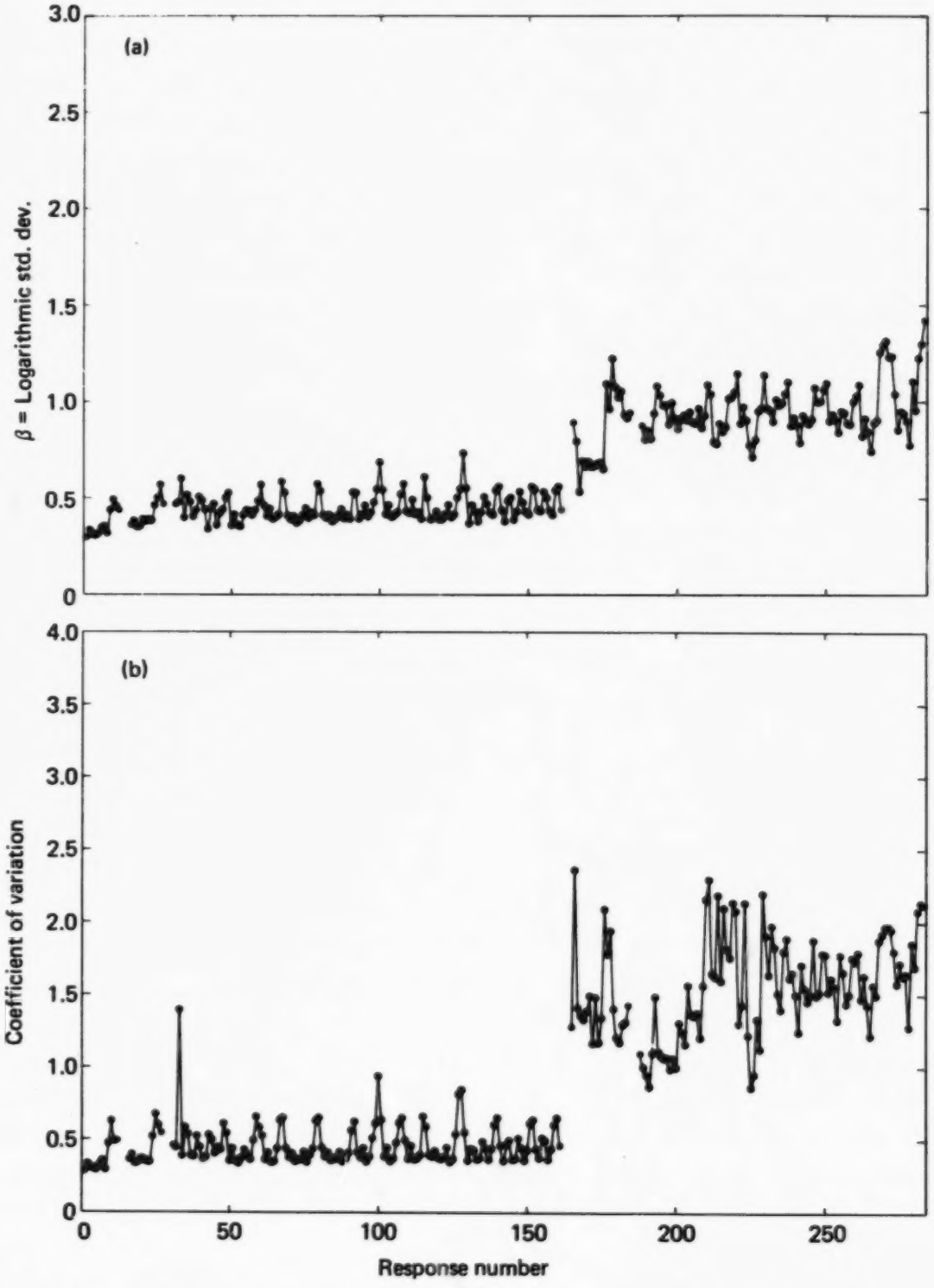


Fig. 14. Uncertainty of responses when all input areas of the SMC are varied: (a) β, logarithmic standard deviation; (b) coefficient of variation.

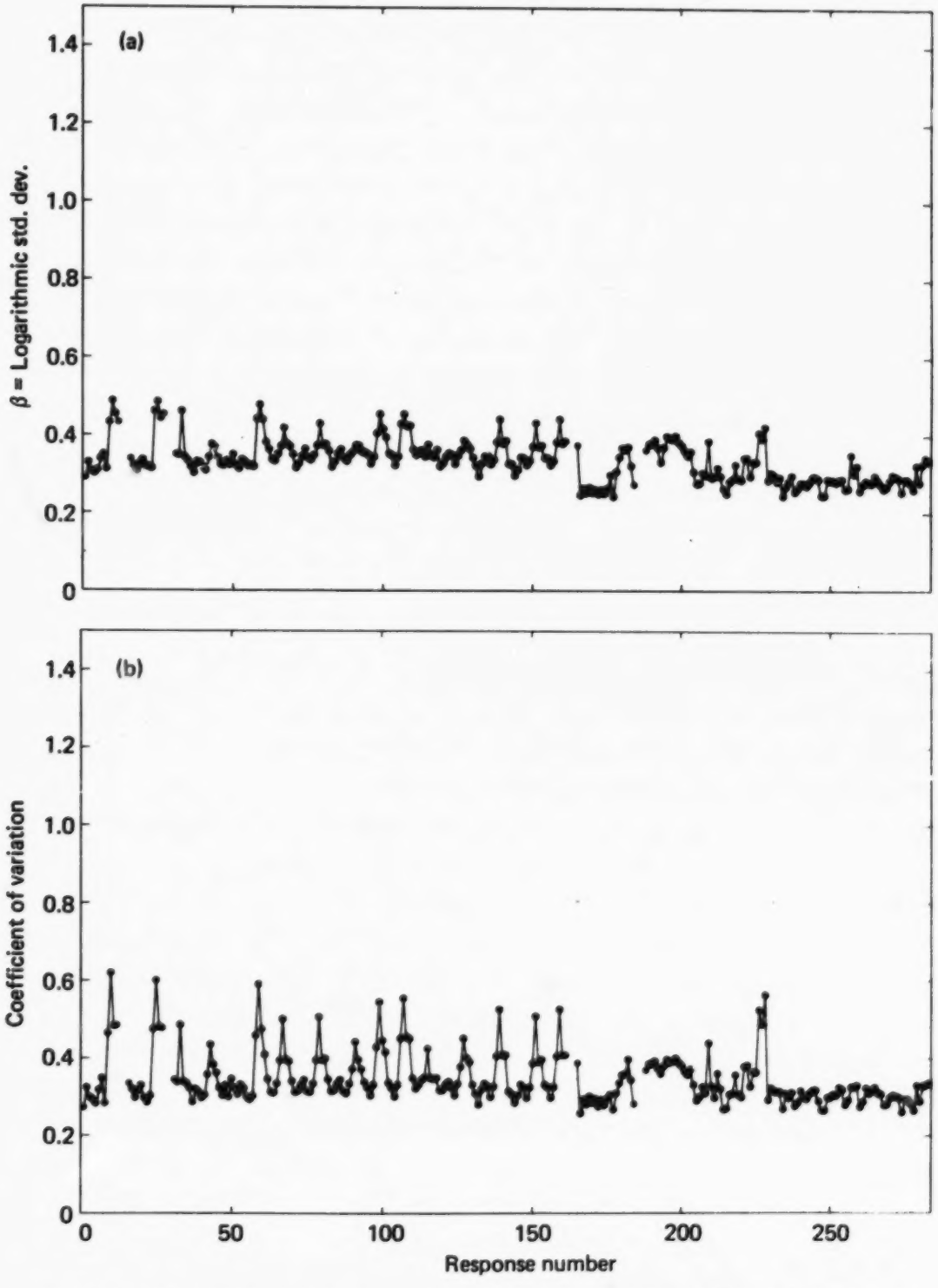


Fig. 15. Uncertainty of responses when only seismic input is varied: (a) β; (b) coefficient of variation.

subsystems are supported at low building elevations, reducing the influence of the structure. Some important nodes are near supports (e.g., heavy valves requiring support), reducing influence from subsystem modal vibrations on the nodal accelerations.

Figures 16 and 17 show the results of subsystem response at one location and the median and standard deviation (β) of the logarithm of responses. The solid line represents the calculated responses while the broken line represents the lognormal fit to the calculated responses. Figure 16 was obtained with all key parameters varied in all areas of the SMC (expt 1). Figure 17 was obtained with the key parameters varied in the seismic input time history only and fixed at median value in other areas of the SMC (expt 2).

The second approach, using first-order uncertainty propagation, was applied to a hypothetical simple subsystem: a single-degree-of-freedom oscillator with variable frequency and damping supported directly on the reactor building basemat, and responding to x-direction motion. Its peak acceleration as a function of its frequency and damping is just the same as the set of basemat response spectra for different damping. Figure 18a shows the mean basemat acceleration response spectra (averaged over 30 time histories and soil property variations) for three damping values. These can be considered as three slices through the response function (as a function of two variables). Taking another directional slice of the response function, Fig. 18b shows the acceleration response as a function of damping, for a fixed frequency of 5.0 Hz.

The contribution to the subsystem's response uncertainty from its frequency or damping uncertainty was calculated as the input parameter's uncertainty times the sensitivity (slope) near the nominal value. The contribution from other inputs up to the basemat level--that is, seismic input and soil-structure interaction--can be seen from Fig. 19, which shows the COV of the basemat spectral acceleration response at each subsystem frequency for a fixed damping at the nominal value of 2%. From the slopes in Fig. 18a and 18b, we see that the acceleration response is more sensitive to subsystem frequency than to damping. For example, an input frequency COV of 0.5 can produce a response COV of about 0.5.

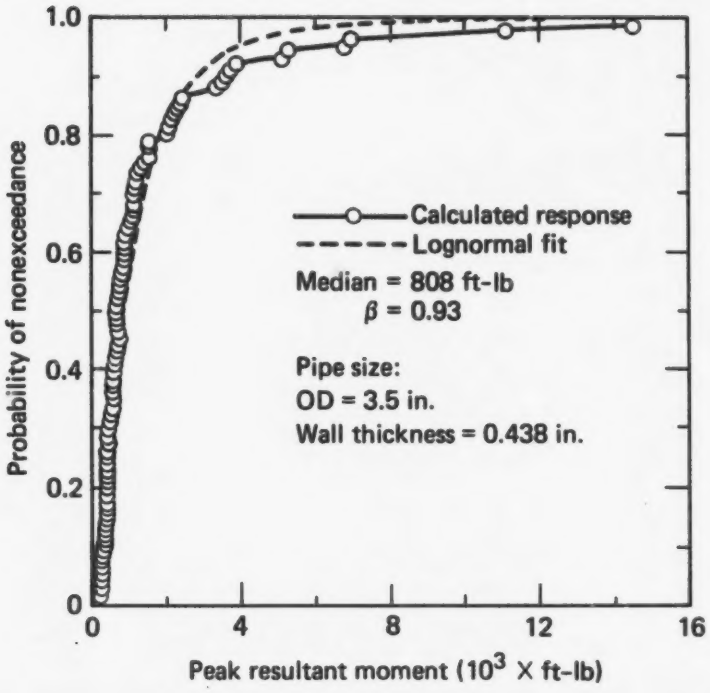


Fig. 16. Cumulative distribution function of the peak resultant moments with all SMC parameters varied.

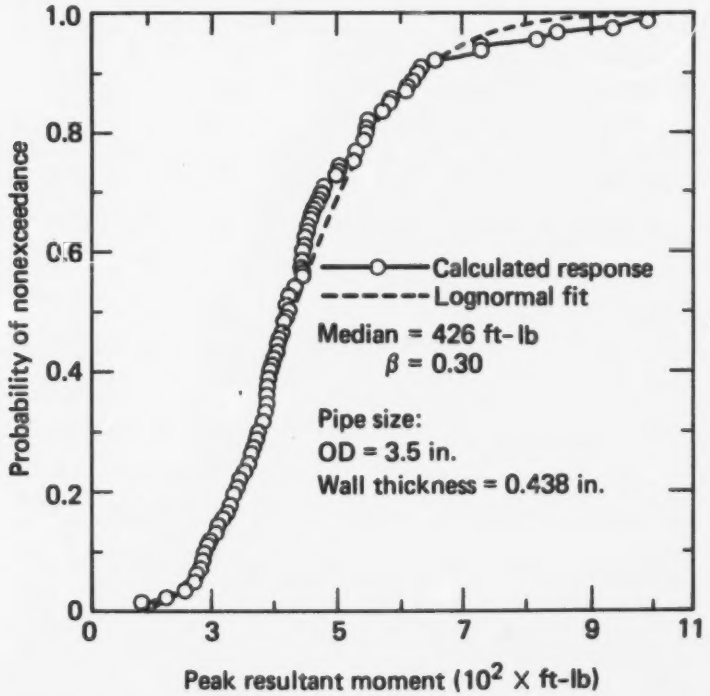
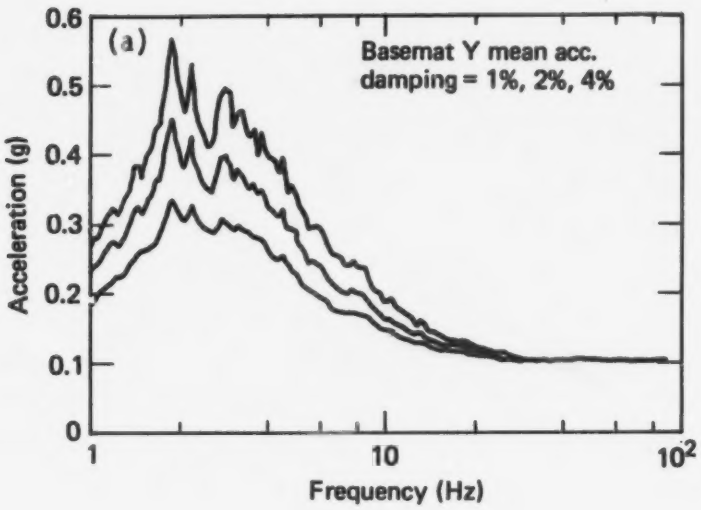


Fig. 17. Cumulative distribution function of the peak resultant moments with only the seismic input time histories varied.



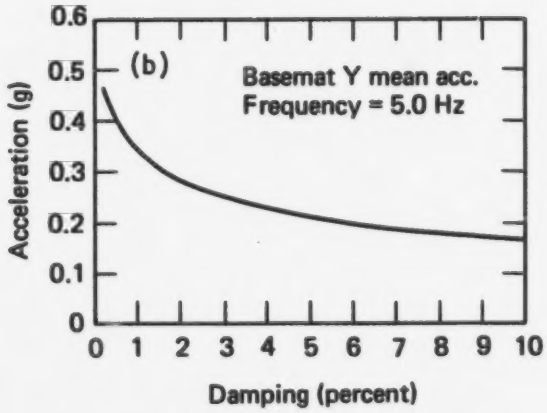


Fig. 18. Acceleration response of a single-degree-of-freedom subsystem on the containment basemat: (a) mean response at three damping values as a function of subsystem frequency; (b) mean response as a function of subsystem damping.

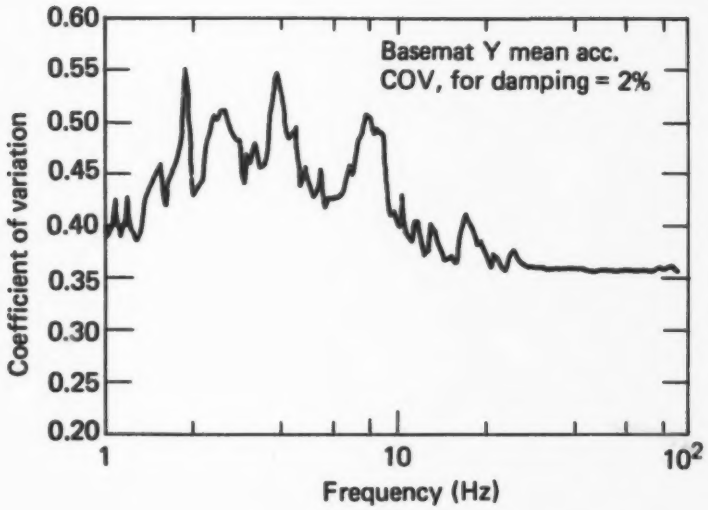


Fig. 19. Coefficient of variation of the acceleration response of a single-degree-of-freedom subsystem as a function of frequency.

SECTION 7: PHASE I TECHNICAL RESULTS

For the singly supported subsystems (such as pumps, turbines, electrical control panels, etc.), the spectral acceleration responses were obtained from major structure responses at the locations where the components were mounted. For multiple supported subsystems such as piping systems, responses were in terms of peak resultant accelerations for valves and peak resultant moments for piping components. These responses were obtained by using the SMACS computer code. Only the responses of the critical piping components (such as tees, nozzles, and elbow/pipe bends, etc.) in the systems identified in the event/fault trees were computed. The subsystem responses and the fragility curves are used in SEISIM to compute the probabilities of component and system failures.

Table 3 shows the important dynamic parameters for the 13 piping models. The number of modes considered in each model was determined by the number of frequencies below the cutoff frequency of 33 Hz. An exception was for the model of RHR pump discharge, where only three frequencies below 33 Hz were extracted. Hence, engineering judgment was utilized to increase the number of modes to ten, which corresponds to cutoff frequencies up to 100 Hz.

To account for the sources of uncertainty, the COVs for piping frequency and piping damping were assigned to be 0.5 and 0.7, respectively; this was in addition to the respective value assigned to the key parameters of uncertainty for other members of the SMC. (See Table 2.)

The seismic hazard curve[23] for the Zion site was discretized into six intervals or "boxes" for our demonstration calculations: 0.15 to 0.30g, 0.30 to 0.45g, 0.45 to 0.60g, 0.60 to 0.75g, 0.75 to 0.98g, and greater than 0.98g. For each interval, 30 earthquake simulations were made. The boxes define the acceleration ranges for which independent calculations, based on the median of each range, were carried through the SSMRP computation procedure (see Table 4). Response plots for 1005 components were generated for each box; therefore, for the Phase I demonstration calculations, only representative plots of interest are shown. Each plot for the on-line computation summarizes the dynamic responses, median, and standard deviations of the logarithm of the response of the piping component to 30 earthquakes in each box. Figures 20 through 25 show the cumulative distribution function of the peak resultant moments at the reactor pressure vessel nozzle of the RCL with the corresponding box.

TABLE 3. Important dynamic parameters for the 13 piping models.

Description	Fundamental frequency (Hz)	No. of modes considered	No. of support motions	No. of components calculated
AFW SG-1A to containment	2.9	36	45	24
AFW outside containment	3.2	93	47	141
SW pump discharge	12.9	20	3	34
SW strainer	16.0	7	3	36
SW to AFW pump	2.0	57	44	145
RHR pump suction	4.3	32	33	58
RHR pump discharge	9.8	10	10	43
RHR and SI-1	3.9	18	21	24
RHR and SI-2	2.7	115	49	190
Charging pump discharge	3.2	87	35	125
Boron inj tank to containment	9.1	8	14	17
RCL and branch lines	1.4	130	127	135
Pressurizer relief lines	3.5	34	28	33
Total				1005

NOTE: Pipe sizes range from 3 to 48 in.

TABLE 4. The six boxes and their corresponding median and ground acceleration ranges.

Box	Median (g)	Range (g)
1	0.183	0.15-0.30
2	0.35	0.30-0.45
3	0.5	0.45-0.60
4	0.65	0.60-0.75
5	0.83	0.75-0.98
6	1.14	>0.98

On each figure, each data point represents the response for one earthquake simulation. Superimposed on the plot (shown as a broken line) is a lognormal distribution fit to the data. Figure 20 should be interpreted as follows: If earthquakes with a peak ground acceleration between 0.15 and 0.30g (Box 1) occur, 90% of them will result in responses below 190,000 ft-lb, or conversely, 10% of them will result in response greater than 190,000 ft-lb. Likewise the median value of 53,974 ft-lb has a 50% chance of being exceeded.

Figure 26 shows the cumulative distribution function of the peak resultant moment responses for Box 1 at the junction of the AFW line and the main feedwater line. By combining Figs. 20 through 25, the peak resultant moments were converted to stresses as plotted in Fig. 27. Figure 27 also shows the design stress for a safe shutdown earthquake. The design value is far above the ninetieth percentile value of our calculations at the Zion SSE level, or conversely, corresponds to a ninetieth percentile value at an acceleration level far above the SSE acceleration. Likewise, Fig. 28 shows the stress distribution by combining the Box 1 moments (Fig. 26) with the other corresponding boxes (not shown). Figure 29 shows typical results of the cumulative distribution function of peak resultant acceleration for a valve in the AFW line. Figure 30 shows the Box 1 dynamic responses, medians, and standard deviations of the logarithm of the response for the AFW piping component at containment penetration P-69. This component is one of the major contributors to the probability of cut-set failure in the event/fault tree analysis of piping systems; however, this component may not be the major contributor to the probability of cut-set failure for a different earthquake. As in the curve in Fig. 30, Figs. 31 through 33 show those components which contribute most to the probability of cut-set failure for different piping systems.

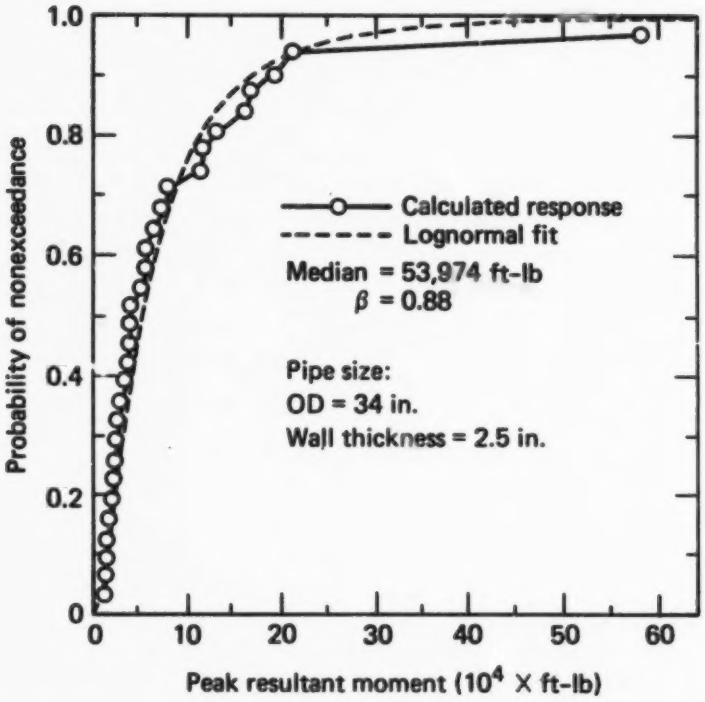


Fig. 20. Cumulative distribution function of the peak resultant moments at the RPV nozzle of the hot leg for Box 1.

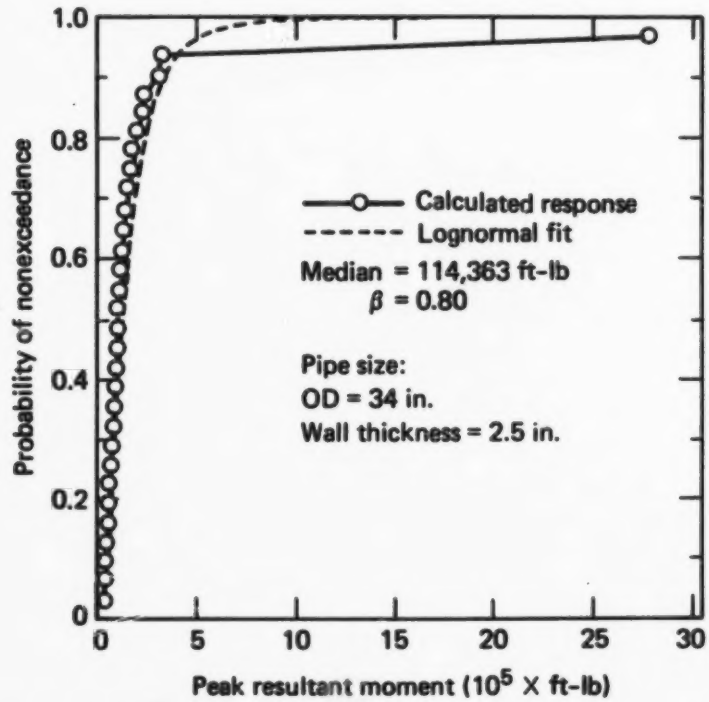


Fig. 21. Cumulative distribution function of the peak resultant moments at the RPV nozzle of the hot leg for Box 2.

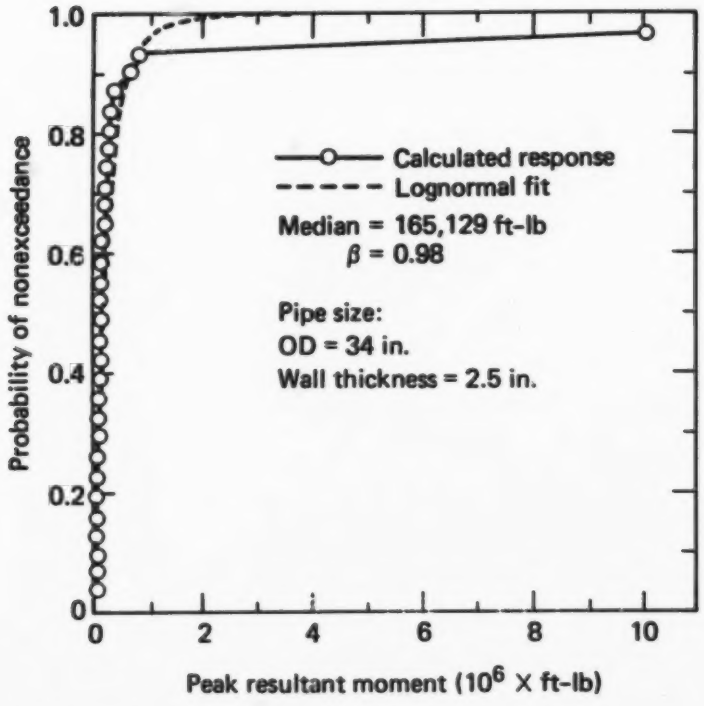


Fig. 22. Cumulative distribution function of the peak resultant moments at the RPV nozzle of the hot leg for Box 3.

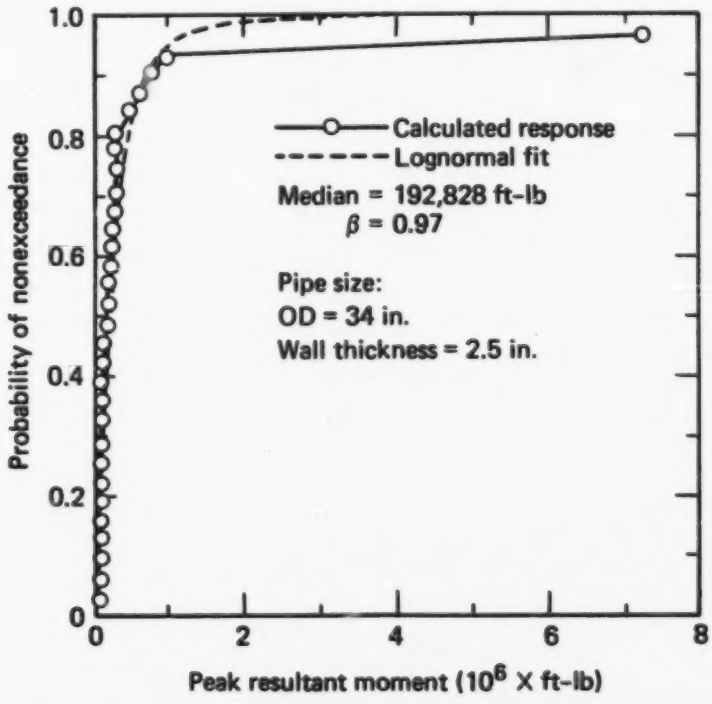


Fig. 23. Cumulative distribution function of the peak resultant moments at the RPV nozzle of the hot leg for Box 4.

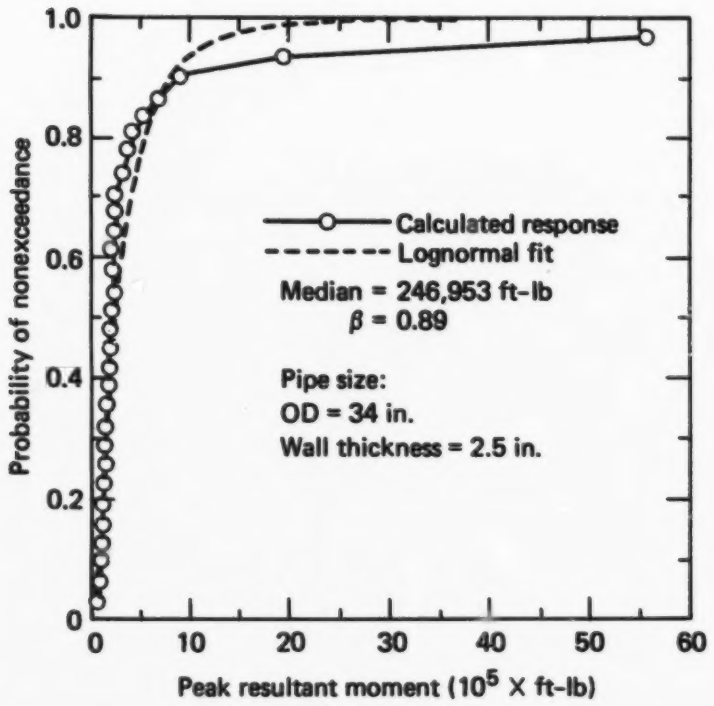


Fig. 24. Cumulative distribution function of the peak resultant moments at the RPV nozzle of the hot leg for Box 5.

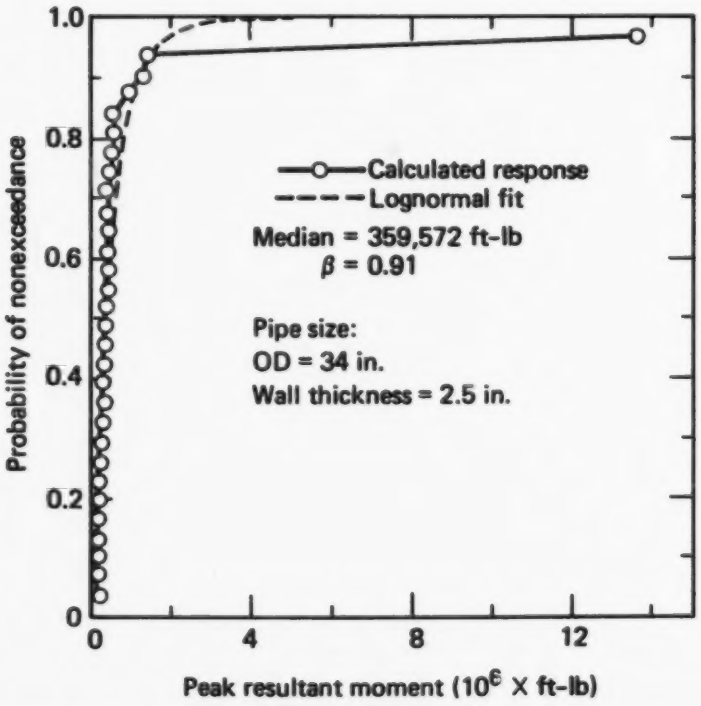


Fig. 25. Cumulative distribution function of the peak resultant moments at the RPV nozzle of the hot leg for Box 6.

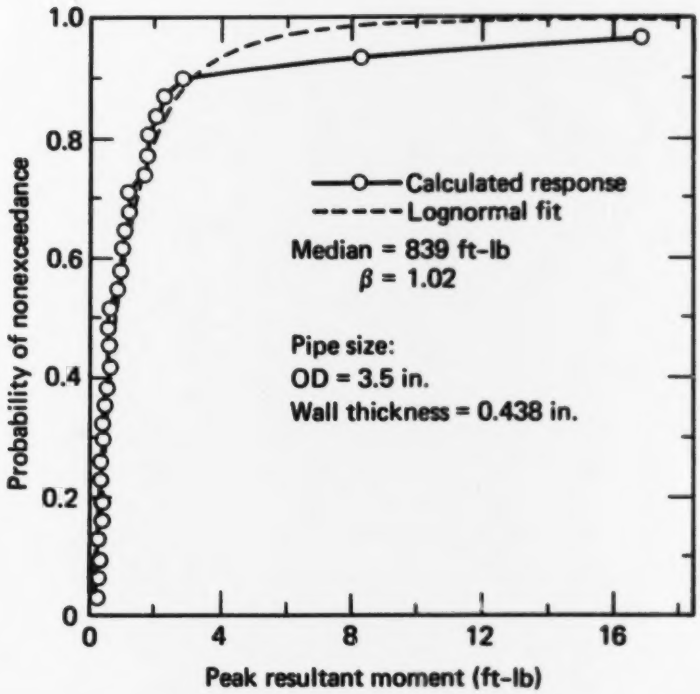


Fig. 26. Cumulative distribution function of the peak resultant moments at the AFW nozzle of the main FW line for Box 1.

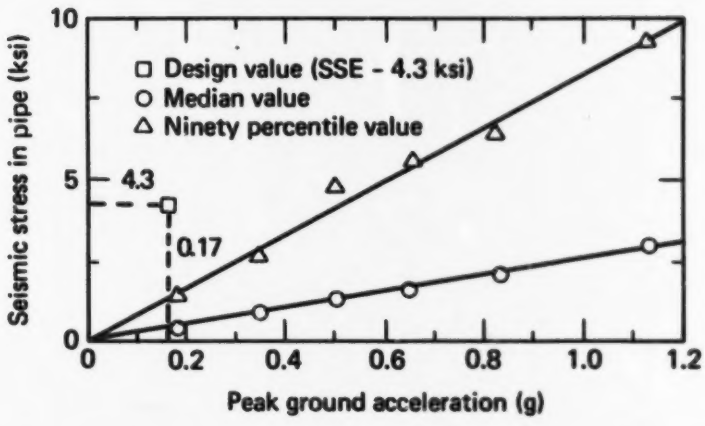


Fig. 27. Seismic stress vs peak ground acceleration at the RPV nozzle of the hot leg loop No. 1.

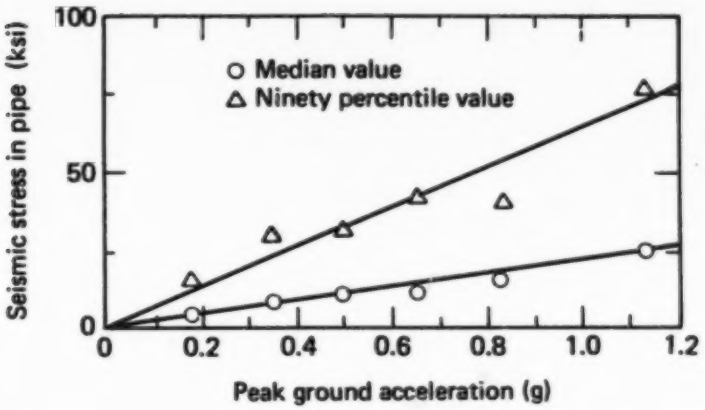


Fig. 28. Seismic stress vs peak ground acceleration at the AFW nozzle of the main FW line.

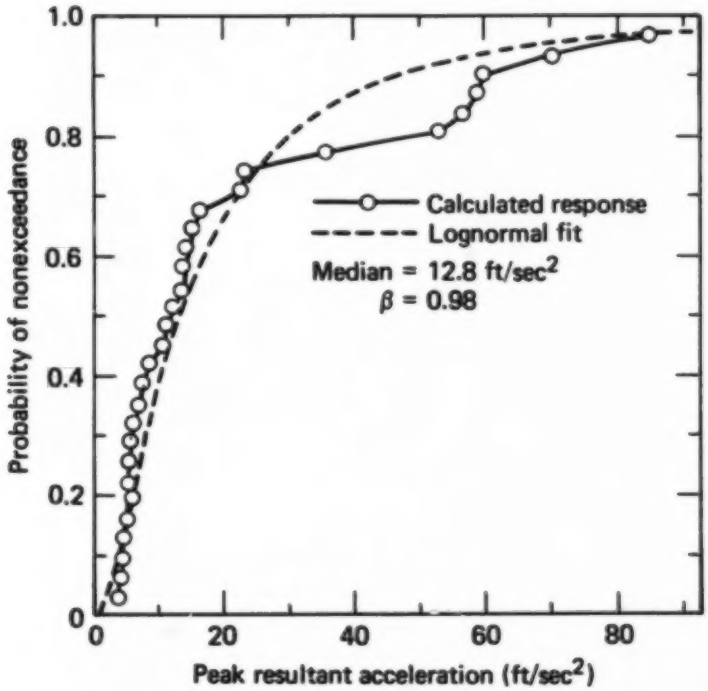


Fig. 29. Cumulative distribution function of the peak resultant accelerations at the check valve of the AFW line for Box 1.

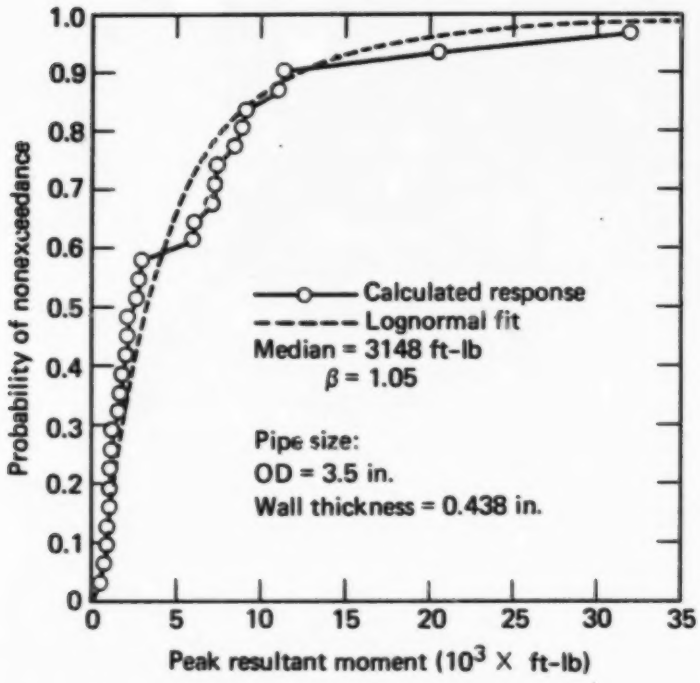


Fig. 30. Cumulative distribution function of the peak resultant moments for one of the highest probabilities of cut-set failure for the AFW cut sets.

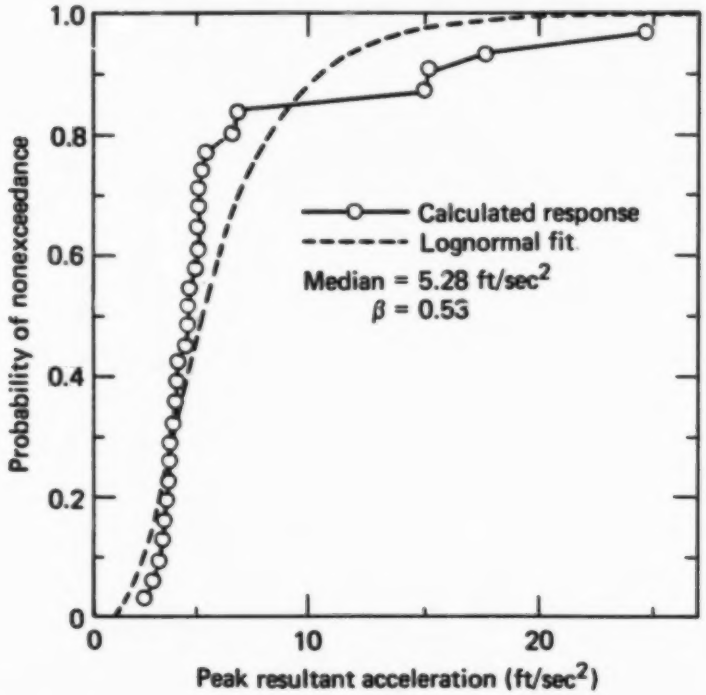


Fig. 31. Cumulative distribution function of the peak resultant accelerations for the highest probability of cut-set failure for the service water system cut sets.

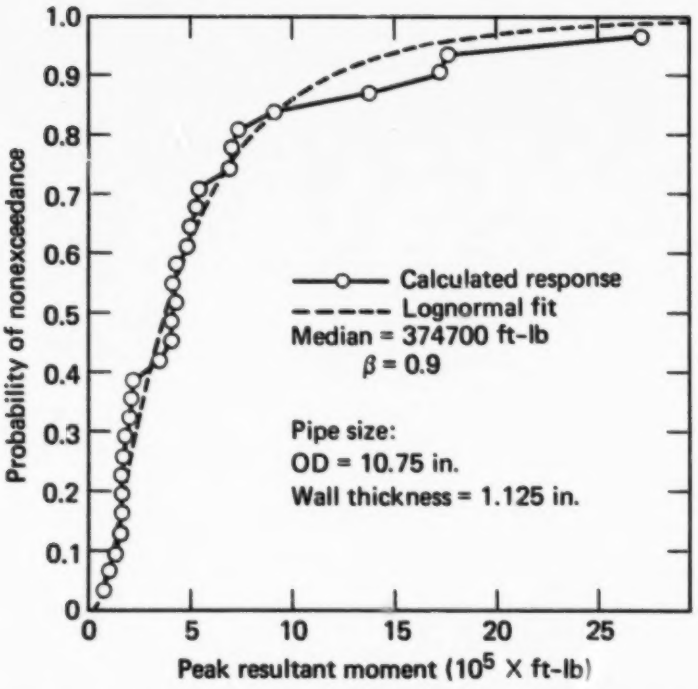


Fig. 32. Cumulative distribution function of the peak resultant moments for the highest probability of cut-set failure for the residual heat removal and safety injection system cut sets.

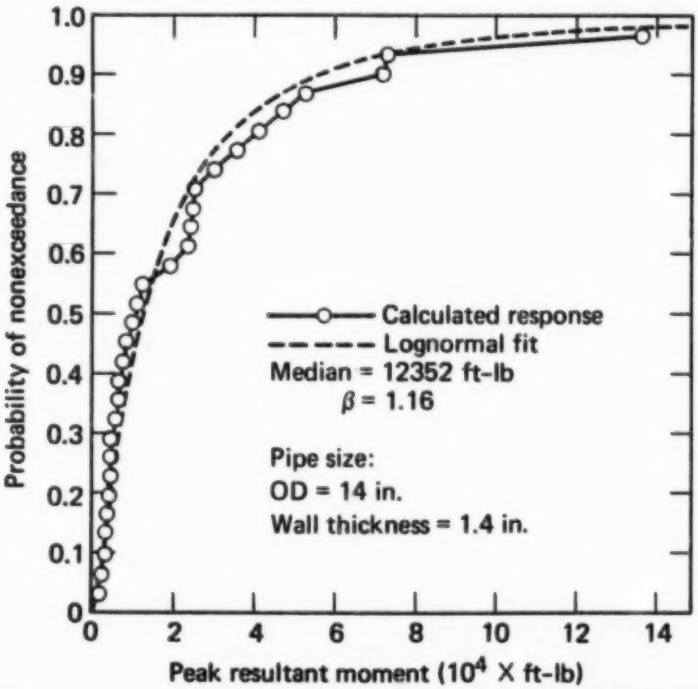


Fig. 33. Cumulative distribution function of the peak resultant moments for the highest probability of cut-set failure for the reactor coolant system cut sets.

SECTION 8: DISCUSSION AND RECOMMENDATIONS

For Phase 1 of the SSMRP, the COVs for piping damping and piping frequency were 0.7 and 0.5, respectively. This caused the wide variation of responses which can be read as a large value of standard deviation of the logarithm of responses. For example, β in Fig. 16 is 0.93, and the extreme response value is about 20 times the median value. If sources of uncertainties are reduced as described in Sec. 6.2, the β value is dramatically reduced to 0.3 (Fig. 17). Accordingly, reduction of the sources of uncertainties shall be considered in the future work. One of the sources that can be identified is the stiffness and failure mode of piping supports. This can be done by incorporating material and/or geometric nonlinearity of piping supports.

In Phase I we have established that the combined soil-structure interactions, structural response, and subsystem response areas contribute more to the uncertainty in the subsystem response than does the seismic input area, assuming an earthquake within the limited peak ground acceleration range, i.e., 0.15 to 0.30g. The seismic input variations were in terms of different earthquake time histories. Further sensitivity studies described in Sec. 6 are under way to rank the individual contributors to the subsystem response uncertainty.* Future sensitivity studies should be done using SEISIM to determine the contributor's impact on cut-set failure uncertainty. Additional studies, using a markedly different site and plant or using simplified models, should be done to explore the degree of site specificity in the SMC uncertainty conclusions.

There are four areas that require further study and development:

- The remaining Zion subsystem modeling, based on fault trees already identified but not analyzed in Phase 1.
- Additional Zion subsystem modeling based on fault trees not identified in Phase 1.
- Investigation of the effects of the assumption of piping support rigidity. In high-stress areas, those supports can experience nonlinear material behavior or buckling due to compressive forces.
- Sensitivity studies of subsystems.

---

*The results completed early in Phase II showed that the subsystem area uncertainty contributes most to subsystem response uncertainty. This work is reported in Ref. 25. Further work to reduce uncertainties in the subsystem area will thus be very beneficial in reducing the response uncertainty.

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16. ABSTRACT (200 words or less)

This document reports on (1) the computation of the responses of subsystems, given the input subsystem support motion for components and systems whose failure can lead to an accident sequence (radioactive release), and (2) the results of a sensitivity study undertaken to determine the contributions of the several links in the seismic methodology chain (SMC)--seismic input (SI), soil-structure interaction (SSI), structure response (STR), and subsystem response (SUB)--to the uncertainty in subsystem response.

For the singly supported subsystems (e.g., pumps, turbines, electrical control panels, etc.), we used the spectral acceleration response of the structure at the point where the subsystem components were mounted. For the multiple supported subsystems, we developed 13 piping models of five safety-related systems, and then used the pseudostatic-mode method with multisupport input motion to compute the response parameters in terms of the parameters used in the fragility descriptions (i.e., peak resultant accelerations for valves and peak resultant moments for piping). Damping and frequency were varied to represent the sources of modeling and random uncertainty.

Two codes were developed: a modified version of SAPIV which assembles the piping supports into groups depending on the support's location relative to the attached structure, and SAPPAC, a stand-alone modular program from which the time-history analysis module is extracted.

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